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Characterising and tracking deterioration patterns of fresh-cut fruit using principal component analysis – Part I

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ABSTRACT

Principal component analysis (PCA) was used to characterise quality deterioration patterns in fresh-cut pineapple, strawberry, kiwifruit and cantaloupe melon during storage. Twenty-seven physiological, biochemical, microbial and sensory attributes, reported as indices of quality, were used to successfully characterise and track deteriorative changes. Freshness for all fruit was characterised by PCA as excellent visual appearance, aroma and firmness. Deterioration was characterised, for the most part, by increased tissue breakdown (exudate and cell permeability levels), firmness loss, increased off-odour development, colour loss (browning and translucency) and high microbial counts. Effects of cultivar and geographic origin were apparent in some fruit. PCA has the potential to track the effects of intrinsic and extrinsic factors of deterioration during storage and could form the basis of future strategies to optimise quality.

1. Introduction

Ensuring quality retention in fresh-cut fruit continues to be a challenge. While storage life and quality are strongly affected by raw materials, severity of processing and storage conditions (Ártés and Gomez, 2006), the precise mechanisms and dynamics of deterioration are incompletely understood. Greater understanding may enable optimised or alternative strategies to be identified and applied. Changes in product appearance and firmness are often first observed, followed by development of off-odours and off-flavours and microbial proliferation. Of particular importance are discolouration (browning, whitening and translucency), loss of firmness (membrane degradation, tissue softening and ion leakage) and decreases in nutritional value (Klein, 1987) coupled with development of off-odours, off-flavours and microbial growth (Brecht, 1995; Varoquaux and Wiley, 1994; Ruiz-Cruz et al., 2010). However these physical, physiological, biochemical and microbial changes occur at different rates and to different extents and are greatly influenced by intrinsic and extrinsic factors, causing significant quality losses between harvest, processing, storage and consumption (Rolle and Chism, 1987; Watada and Qi, 1999; Mahdavian et al., 2007; Safizadeh et al., 2007; Singh et al., 2007; Kazemi et al., 2011; Shirzadeh and Kazemi, 2011).

Significant effects of production locality and/or cultural practices have been noted in many fruit (Blanpied et al., 1987; Rowell, 1988) attributable to the fact that worldwide fruit production has expanded greatly in terms of traditional and new locations of diverse climatic conditions, cultural practices and harvesting techniques. Therefore there is a need for a dynamic overview of the complex continuous quality tests of traditional evaluation systems, where datasets can be simplified to graphical representations for quality interpretation. Such systems are emerging (Rocha et al., 2010; Infante et al., 2011; Hurtado et al., 2012; Chen et al., 2013; Dong et al., 2013; El Kar et al., 2013; Wilson et al., 2013).

In postharvest science, principal component analysis (PCA) is an emerging method for routine data analysis (Reichel et al., 2010; Kienzle et al., 2011). It is regarded as an unsupervised method of multivariate analysis, meaning that the model is not guided in a predetermined direction. Furthermore, PCA is viewed as an iterative measure of 'real world' observation through which a dataset is resolved into a matrix in the form of principal components (PCs) that can be handled by classical statistic methods, visualised and interpreted to extract the particular information required (Wang et al., 2012).

By applying PCA to a range of sensory, physical and chemical data, clearer patterns may emerge that cannot be seen with individual measurements over large data-sets. One way of detecting such patterns is to plot the quality attributes in multidimensional space, the dimensions of which are the new derived variables. In this case, the attributes are ordered along each retained principal

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component (PC) with the distance between each one representing their biological dissimilarity (Holland, 2008).

Typically, only the first two PCs accounts for meaningful variance, hence only PCI and PCII are commonly retained and interpreted in simple structure biplots. Furthermore, because all units of measurement in quality evaluation are different, the data is frequently centred and standardised to unit variance to have equal weight in analysis, with the resulting illustration referred to as a correlation matrix. The loadings produced will show a similar pattern, although their absolute differences will differ, with variables plotted along PCI and PCII displaying different constructs sharing the same conceptual meanings respectively, i.e. good quality and poor quality. In terms of interpretation, a negative loading for an attribute on PCI, for example, means that along PCI, all negative loadings correlate positively with other variables in the same axis plane and negatively with other variables loaded positively.

However, although it is widely used and accepted in postharvest food science and industry, PCA is relatively unpractised when it comes to quality evaluation and factor analysis. The dynamic output from such a system are often visualised as intricate patterns that can neither in detail be predicted nor exactly interpreted by users.

The aim of the present study was to evaluate the effectiveness of PCA in characterising quality changes in a number of fresh-cut fruit. Deterioration patterns due to cultivar and geographic origin differences were also determined with a view of optimising intrinsic factors affecting fresh-cut fruit quality.

2. Materials and methods

2.1. Plant materials

Whole fruit were collected from a local wholesaler (Richardson's Fruit and Vegetables, Limerick, Ireland) the day before each trial and stored at 4 °C (for a maximum of 15 h for chilling sensitive commodities) until processed. Intrinsic factors (geographical variation of fruit origin and cultivar) of intact fruit studied are shown in Table 1.

2.2. Fresh-cut processing and packaging

Fresh-cut fruit were processed at room temperature (~22 °C). Peels, husks, stems and hulls were manually removed using a stainless steel knife and the fruit were cut to size as required. All fruits were cut into 25 mm (pineapple and melon) and ¼ (kiwifruit) sizes while strawberries were de-hulled and halved. All samples (150 g) were placed in rigid polylactic acid (PLA) trays within pillow packs (412.9 cm^2) and sealed using an impulse bench-top heat sealer (Relco, UK Ltd., England). A high barrier laminate flexible film (PET12/PE55) with O_2 and CO_2 permeabilities of 62,814 and 212,776 ml μm/m^2 day atm was used to make the pillow packs (Amcor Flexibles, Gloucester, UK). This resulted in product modification of the atmosphere within packs.

2.3. Quality testing

Quality assessments on fresh-cut packaged fruit were performed on day 0, 1, 4 and 7 of storage.

2.3.1. In-pack gas composition

The percent concentration of atmospheric gases within packs was measured at room temperature (~20 °C) using a gas-space analyser (Systech Instruments, UK) fitted with an air-tight syringe. The mean values of duplicate O_2 and CO_2 concentrations were recorded and the experiment repeated twice.

2.3.2. Moisture loss (%)

Percent weight loss was calculated using the method from Moneruzzaman et al. (2008) and expressed as gram loss per 150 g fresh-cut weight using the following equation:

$$\frac{\text{Initial weight of pack} - \text{Weight on day analysis} \quad (\text{g})}{\text{Initial weight of pack} \quad (\text{g})} \times \frac{100}{1}$$

2.3.3. Drip-loss, exudate and cell permeability

The volume of free liquid released during storage (driploss) was recorded as mL/150 g fresh weight. Exudate levels were quantified using the method by Carlin et al. (1990) with slight modifications, and recorded as grams per 100 g fresh weight. Cell permeability was determined by monitoring leakage of UV-absorbing solutes as reported by Picchioni et al. (1994) with slight modifications. The absorbance of the clarified solution was measured at 260 nm against distilled water (UV/Vis Spectrophotometer, Varian Cary 100, Agilent Technologies Ltd., Dublin, Ireland).

2.3.4. Percent soluble solids

Percent soluble solids were measured in clear fruit juice from homogenised fruit pieces using an Atago Digital Pocket Refractometer (Atago Co., Ltd., Tokyo, Japan).

2.3.5. Tissue pH and titratable acidity

Tissue pH was recorded from homogenised fruit pulp. Clear juice (10 mL) was mixed with 10 mL of distilled and deionised water was measured using a Jenway 3510 pH meter. Titratable acidity was calculated as citric acid by titrating juice samples to pH 8.2 using 0.1 N NaOH.

2.3.6. Colour

Surface colour of fresh-cut fruit was determined using a Minolta chromameter 5081, fitted with an 11-mm aperture and a D_{65} illuminant (Konics Minolta, Sensing Inc., Osaka). Three measurements were taken at random locations on each of the fruit samples, and this was replicated three times. CIE L^*, a^* and b^* values were determined and presented herein.

2.3.7. Texture

Firmness was determined using a TA.XT Plus Texture Analyser (Stable Micro Systems, Surrey, UK) fitted with a 6 mm flat tipped cylindrical probe. The force required to penetrate (F) a piece of fruit was recorded as both the maximum and mean force in Newtons (N). The fresh-cut pieces were of uniform shape and size to allow for repeated accuracy of results. Using the Kramer Shear Cell and Extended Craft Knife (pineapple only) attachments, the maximum force, area and mean force required to shear (S) through 150 g of fruit samples, in duplicate, was recorded in Newtons (N) as an index of product firmness.

2.4. Microbial enumeration

The different media used were prepared, plated and stored according to manufacturer's instructions (Oxoid Ltd., Basingstokes, UK). On each sampling day, 10 g of fruit was aseptically removed from each pack and homogenised with 90 mL of 0.1% peptone water at high speed for 120 s. Serial dilutions (10^{-1} to 10^{-4}) were prepared by mixing 1 mL of the homogenate liquid with 9 mL of 0.1% peptone water. Total viable counts (mesophiles and psychrophiles) and yeasts and moulds were prepared in the following way: aliquots (100 μl) of each serial dilution were applied on to the surface of appropriate media and were surface spread in duplicate using an inoculation spreader. For lactic acid bacteria (LAB), media pour plates were prepared whereby 100 μl of sample was added to the media followed by a molten overlay of media (50 °C). Total

Table 1
Fruit types, cultivars/variety, countries of origin and class used.

Fruit	Cultivar/variety	Country of origin	Class	Season
Pineapple	Del Monte Gold Extra Sweet	Costa Rica	Extra	Autumn
	Ananas comosus L. Merr MD2	Brazil		
Strawberry	*Fragaria* spp.			Summer
	Elsanta	Ireland	I	
	Festival	Egypt	I	
	Orly	Ethiopia	I	
	Camarosa	Spain	I	
	Camarosa	Morocco	I	
Kiwi	*Actinidia deliciosa* cv			Autumn
	Hayward	New Zealand	I	
	Hayward	Italy	I	
	Hayward	Brazil	I	
Melon	*Cucumis melo* L. var *reticulatus*	Costa Rica	I	Winter
	Cucumis melo L. var *reticulatus*	Brazil	I	
	Cucumis melo L. var *cantalupensis*	Italy	I	

viable count plates for mesophiles and psychrophiles were incubated at 35 °C and 4 °C for 48 h and 7 days respectively, LAB plates for 48 h at 35 °C and yeast and mould plates for 5 days at 20 °C. Following incubation, colony-forming-units (CFU) were counted on plates that contained between 20 and 200 CFU. Results were expressed as colony-forming-units per gram (CFU/g) of sample.

2.5. Sensory evaluation

Analytical descriptive tests were used to evaluate the sensory quality attributes of fruit packs. The quality attributes examined were overall visual appearance, colour, aroma, off-odour, texture, and overall acceptability. Evaluation was performed by an untrained sensory panel which consisted of 12 judges (8 female and 4 male), all members of the Life Science Department, University of Limerick. Before the start of each sampling day, panel members were familiarised with the product and scoring procedure. Panellists were then randomly grouped into pairs and given 1 sample pack (as is) to evaluate against that of a fresh-cut sample (control) in terms of the attributes mentioned above. External colour was assessed using descriptors developed by Kader and Cantwell (2010). For visual appearance and overall acceptability, fresh-cut fruit were evaluated under fluorescent lighting using a 9-point rating scale, where a score of 9 indicated the sample was excellent, 7 represented very good, 5 acceptable/fair, 3 poor and 1 extremely poor. Evaluation of aroma was performed using quantitative descriptive sensory analysis techniques (Kader and Cantwell, 2010), where; 9 = excellent, normal characteristic aroma, 7 = very good, normal to slightly off, 5 = limit of marketability, 3 = fair, limit of usability, strong off-odours, slightly anaerobic, becoming offensive and 1 = poor, inedible, very strong off-odours, very fermented. In addition to quantitative descriptive aroma analysis, panellists were also asked to comment on the typical fresh-cut aroma of raw materials used before packaging. A list of the common aroma characteristics ascribed by the panellists for each of the fresh-cut fruit evaluated is presented in Table 2. For texture evaluation panellists were asked to rank firmness (touch) by marking a 100 mm line with unanchored terms where a score of 1 mm = extremely soft while a score of 100 mm = extremely firm. Quantitative results were obtained by measuring the distance from zero to the mark.

2.6. Statistical analysis

Multifactorial experiments were conducted in duplicate and repeated twice. Data for quality deterioration parameters were processed by analysis of variance (ANOVA, repeated-measures, SPSS 19, IBM, Chicago) with all factors in each experiment reported as fixed effects ($p < 0.05$). Microbial populations and sensory parameters were individually analysed by two-way analyses of variance (paired *t*-test). For sensory parameters, panellists were reported as random effects and treatments as fixed effects ($p < 0.05$). Tukey's pairwise comparison test was used for differences between individual treatments ($p < 0.05$).

For each experiment, PCA was performed on all quality and sensory variables (Canoco 4.5; Waigeningen, UR, NL). The analysis was performed on the response of 27 variables to six to ten sample treatments, each the mean of four replicates. All variables were mean centred and standardised (scaled) to unit variance prior to analysis, i.e. correlation matrix. For each component of the PCA, a score for each sample was calculated as a linear combination for each physiochemical, sensory and microbial parameter measurements. The contribution of each parameter to the PCA score was deduced from the parameters loading for the factor. As PCA is performed on a matrix of Pearson Correlation Coefficients, the data should therefore satisfy the assumptions for this statistic. However, it is often desirable to assess this reliability by computing coefficient alpha as an index of internal consistency and reliability. For that reason, Pearson's correlation (ρ) was performed using SPSS 20, (IBM, Chicago, IL, USA) to better understand the association between monotonic quality (ratio) and sensory (ordinal) variables within a dataset and test the reliability of the technique. Where appropriate; (ρ) ranged from inverse (−1) to positive (+1) with small ($0.1 \le |\rho| < 0.3$), medium ($0.3 \le |\rho| < 0.5$) and large/strong ($|\rho| \ge 0.5$) effects noted.

3. Results

3.1. Processes of deterioration

Principal component analysis was carried out on the correlation matrix produced from twenty-seven quality attributes, previously identified as contributing to the quality deterioration of fresh-cut fruit. The factor loadings for the different quality ratings were plotted based on the first two principal components (PCs) with attributes and samples illustrated as vector angles and symbols respectively. PCI accounted for the greatest amount of the total variance (inertia) meaning that (under typical test conditions) PCI was correlated with many of the observed variables loaded on that component. PCII was uncorrelated with PCI and accounted for the largest amount of total variance in the dataset not accounted for by PCI. The proportion of variance accounted for was deduced using the cumulative percent of variance criterion for determining the number of PCs to retain. For the current analysis the cumulative percent of variance must have accounted for at least 90% of

Table 2
Intrinsic characteristics of intact fruit used.

Type/source	Origin	Cultivar	Physiological age		Aroma[c]	Firmness, *N*	Soluble solids, %
			External colour,[a] %	Ripeness class			
Pineapple[a]	Costa Rica	Del Monte Gold	25–50	Ripe (2–3)	(8) Sweet, Pineapple	7.6	12.7
	Brazil	Extra Sweet	25–50	Ripe (2 to 3)	(7) Sweet, Pineapple, Tart	7.3	12.3
Strawberry[b]	Spain	Camarossa	5	Ripe (5)	(8) Strawberry, Sweet, Fresh	11.1	8.5
	Morocco	Camarossa	4–5	Ripe (5)	(8) Strawberry, Sweet	9.6	9.2
	Egypt	Festival	5	Ripe (5)	(9) Strawberry, Fresh	7.0	9.2
	Ethiopia	Orly[d]	6	Ripe (5)	(6) Strong, Strawberry, Musty	4.4	9.1
	Ireland	El Santa	5	Ripe (5)	(8) Sweet, Strawberry, Fresh	2.4	8.3
Kiwifruit[b]	Italy	Hayward	3	Ripe (4)	(9) Grassy, Green, Sweet,	1.5	7.5
	New Zealand	Hayward	3	Ripe (5)	(9) Green, Grassy, Fresh	2.8	7.3
	Brazil	Hayward	3	Ripe (5)	(8) Green, Grassy, Fresh		
Cantaloupe Melon[b]	Costa Rica	N/A	5	Ripe (5)	(9) Pungent, Green, Musky	8.2	7.7
	Brazil	N/A	5	Ripe (5)	(8) Pungent, Musky, Sweet	6.5	7.1
	Italy	N/A	5	Ripe (5)	(8) Melon, Sweet, Musky	7.3	6.5

[a] External shell colour was recorded against a Dole pineapple colour chart.
[b] External shell colour was recorded against UC Davis colour charts (Kader and Cantwell, 2010).
[c] Numbers in brackets depict ripeness class and aroma scores.
[d] Signs of mould in some packs.

inertia in order to be retained and subsequently interpreted. *Following this, the orthogonal biplot was reviewed for interpretability*. The proportions of variance produced for biplots of each fruit type are presented in Table 3.

In order to assess whether categories of variables were different from, or positively/negatively associated with each other, confidence ellipses were drawn around them (Fig. 1a–d). These ellipses enclosed a group of related variables and/or identified groups of related variables across each matrix.

A consistent trend was observed for all fruit studied in that the rotated factor pattern demonstrated a simple orthogonal structure with variable loadings on PCI and PCII measuring different constructs respectively. Furthermore, variables loading on PCI and PCII respectively share the same conceptual meaning, e.g. PCI refers to good quality attributes while PCII refers to poor quality attributes, with the exception of cantaloupe melon. Observations close to each other in the space of a PC are said to have similar characteristics. Similarly, variables whose unit vectors are close to each other are said to be positively correlated, meaning that their influence on the positioning of samples is similar. Variables distant from each other across an axis plane are defined as being negatively correlated. Poor quality attributes positively associated with increased deterioration were identified as increased microbial counts, increased cell permeability and exudate levels, increased off-odour development, CO_2 accumulation and discoloration. Good quality attributes were reported as good appearance, aroma, firmness and overall acceptability and in most cases were inversely correlated with the poor quality attributes previously noted. Coefficient alpha values (ρ) reported indicate the reliability of PCA interpretation using the biplot alone.

Irrespective of treatment, all samples moved in a similar pattern during storage indicating diminished quality and increased deterioration (see also Finnegan and O'Beirne, 2014). As anticipated and as illustrated by small vector angles within the same component plane, scores for acceptability of appearance, aroma and firmness were highly correlated with overall acceptability for all fruits. For fresh-cut pineapple, poor quality attributes such as increased drip-loss, weight-loss and exudate were positively loaded on PCII, while good quality attributes such as fresh appearance ($\rho = 0.869$), firmness ($\rho = 0.380$), and aroma ($\rho = 0.780$) were highly correlated with overall acceptability and negatively loaded. Tissue breakdown, reported as increased exudate and cell permeability levels, were shown to be negatively correlated ($\rho = -0.612$) with instrumental firmness measurements suggesting a direct relationship with deterioration.

For fresh-cut strawberry, poor quality attributes such as increased cell permeability, microbial counts (especially yeasts and moulds and lactic acid bacteria) and off-odour were positively loaded on PCI, while good quality attributes such as visual appearance ($\rho = 0.869$), aroma ($\rho = 0.780$) strongly correlated with overall acceptability, and negatively loaded. Firmness loss (both instrumental and sensory) was negatively loaded in PC I and II respectively, with sensory firmness negatively correlated with overall acceptability.

For fresh-cut kiwifruit, discoloration (loss of greenness observed as loss in luminosity (L^*) and greenness (a^*) with increased yellowness (b^*)) and loss of firmness were highly indicative of increased deterioration. There were strong correlations between appearance ($\rho = 0.800$), firmness ($\rho = 0.901$) and overall acceptability. Moreover, increased cell permeability levels were positively correlated with instrumental firmness levels ($\rho = -0.800$), again suggesting a relationship.

Interestingly, unlike other fruit, quality changes in fresh-cut cantaloupe melon occurred along PCII, moving from positive position to negative during storage. The positioning of loadings so closely together would suggest minimal quality change during storage. The positioning of sample scores on the far left would also suggest that fruit pieces were less affected in terms of quality

Table 3
Proportion of cumulative percentage variance and inertia for biplots construed for each fruit type and treatment.

Effects measured	Fresh-cut fruit	PC I (%)	PC II (%)	PC III (%)[b]	PC IV (%)[b]	Inertia (%)[a]
Geographical variation of fruit origin and cultivar	Pineapple	55.8	30.2	10.2	2.4	98.6
	Strawberry	50.5	35.4	6.7	3.5	96.1
	Kiwifruit	49.0	33.9	11.6	3.5	98.0
	Cantaloupe Melon	65.8	24.3	8.5	0.9	99.5

[a] Inertia is a measure of variation or 'spread' within a correlation matrix, i.e. the total variance of the dataset (Husson et al., 2008).
[b] Data disregarded for subsequent interpretation.

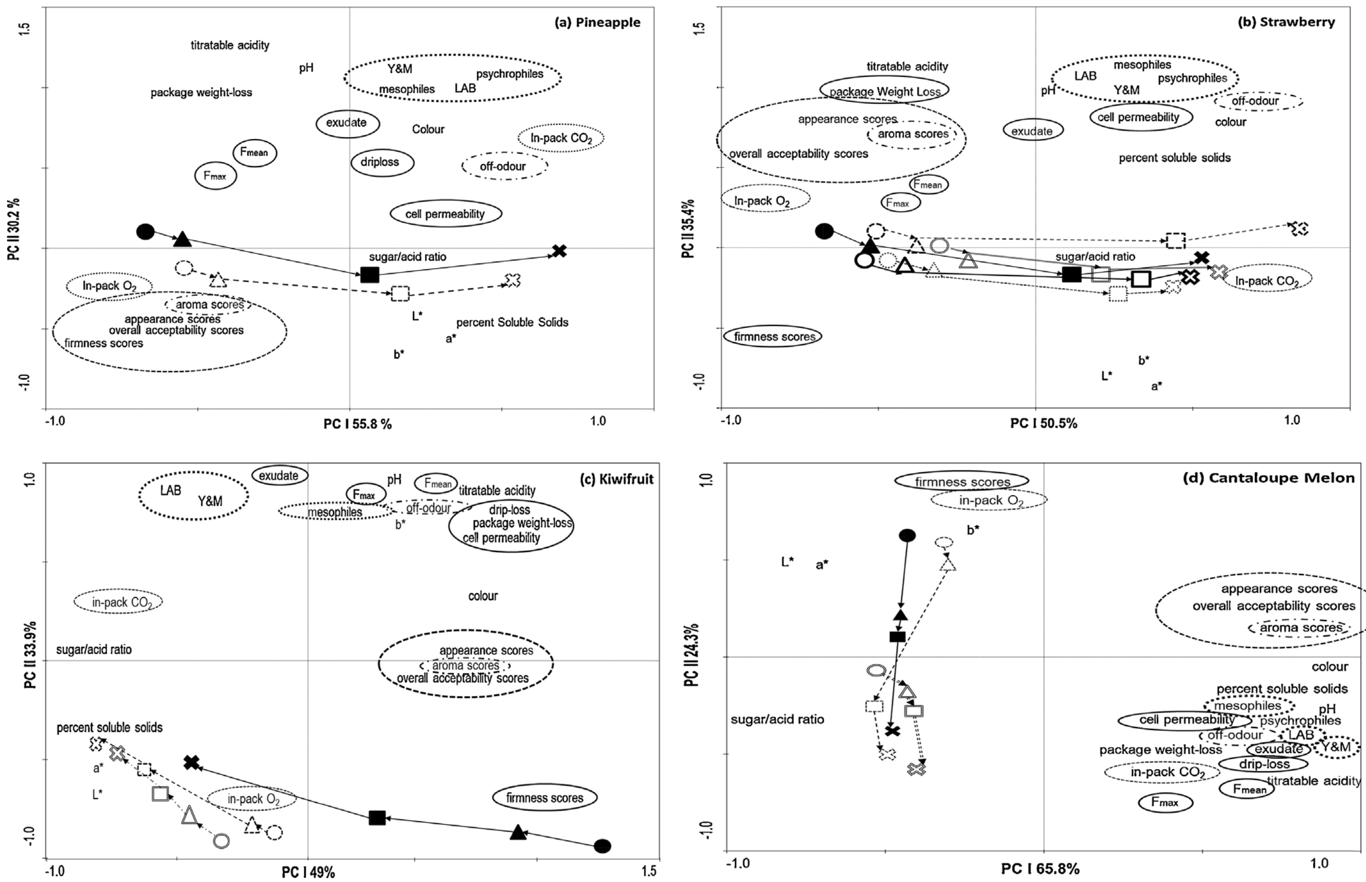

Fig. 1. Principal component analysis (PCA): Biplot of the loadings and scores of PC1 and PC2 after analysis of effects of geographical origin and cultivar on quality evaluation attributes for (a) fresh-cut pineapple, (b) fresh-cut strawberry and (c) fresh-cut kiwifruit (d) fresh-cut cantaloupe melon during 7 day storage at 4 °C. *Key of abbreviations (attributes):* CO_2 (carbon dioxide), O_2 (oxygen), F (puncture probe firmness – 6 mm), S (shear firmness), max (maximum firmness, Newton), mean (mean firmness, Newton), LAB (lactic acid bacteria), Y&M (yeasts and moulds), L^* (CIE L^* lightness-darkness), a^* (CIE a^* green-red) and b^*(CIE b^* blue-yellow). Key to confidence ellipses: - - - - - microbial traits; — firmness traits, ····· O_2/CO_2, —·— aroma/off-odour, – – – sensory traits. Fresh samples evaluated initially on Day 0 ●; Day 1 ▲; Day 4 ■; and Day 7 ✖. *Key of symbols (samples):* Pineapple: ● (Brazil) and ◌ (Costa Rica). Strawberry: ○ (Spain), ◌ (Ireland), ◌ (Morocco), ● (Egypt) and ◎ (Ethiopia). Kiwifruit: ◌ (Brazil), ◎ (Italy) and ● (New Zealand). Cantaloupe melon: ● (Costa Rica), ◌ (Brazil) and ◎ (Italy).

change than other fruits. An exception to loadings is the positioning of CIE L^*, a^* and b^* values and sensory firmness which appeared to be the greatest attributes affected; observed as loss of luminosity and orange hue and loss of firmness in favour of increased colour change (sensory colour) and increased instrumental firmness. Furthermore, aroma scores were highly correlated with acceptability ($\rho = 0.736$). Furthermore, increased off-odour ($\rho = -0.865$) and microbial counts ($\rho = -0.800$) were highly associated with increased deterioration during storage. Sugar/acid ratio and percent soluble solids were inversely correlated ($\rho = -0.642$) indicating the importance of sweetness in melon quality compared to the other fruits studied.

3.2. Effects of origin and cultivar

Depending on the source of the whole fruit used for fresh-cut fruit processing and/or the cultivar, sample loadings were separated out along the PCs according to their initial quality and patterns of deterioration. The data show the relationships between the geographic origin of the raw material, the cultivar (fresh-cut strawberry only), storage time and overall quality loss (Fig. 1a–d).

In the case of pineapple, fresh-cut Del Monte Gold Extra Sweet from Costa Rica and Brazil were compared. Fresh-cut fruit from both sources displayed similar patterns of deterioration during storage, with Costa Rican grown fruit having slightly better quality throughout. Deterioration was slowest between day 0 and day 1, and more rapid thereafter, showing increasing cell permeability, in-pack CO_2 accumulation, off-odour development and microbial counts, slightly more so for Brazilian grown fruit.

In the case of strawberry, the cultivar '*El Santa*' (from Ireland), '*Camarosa*' (from Spain and Morocco) '*Festival*' (from Egypt) and '*Orly*' (from Ethiopia) were compared. All samples quickly lost their initial fresh-cut quality characteristics and, by day 4, were characterised as having very high in-pack CO_2 levels, high microbial counts, decreased acceptability and darkening red hue. Irish *El Santa* strawberries had the greatest rate and extent of deterioration as demonstrated by the positioning of the sample loadings across the axes planes. Compared to the other cultivars, Camarosa samples were located low in the axis plane which may indicate fruit of slightly poorer quality.

In the case of kiwifruit, fruits of the cultivar '*Hayward*' were compared from three sources and analysed over 2 months (August and October). Fresh-cut New Zealand fruit had best initial quality, and retained good appearance, aroma, firmness and acceptability for longer. Scores were located further down to the right of the good attribute plane, moving towards the poor attribute plane as storage progressed. Fresh-cut Italian and Brazilian fruit had initially poorer quality, and were positioned further to the left of the plane, characterised as having reduced appearance, firmness and overall acceptability. Fresh-cut New Zealand kiwifruit deteriorated later

in storage, the greatest rate of deterioration from day 4 to day 7. By contrast, Brazilian kiwifruit had greatest quality loss early, from day 1 to day 4.

Cantaloupe melons were studied from three sources, *reticulantus* from Costa Rica and Brazil, and *cantaloupensis* from Italy. Fresh-cut Costa Rican melons initially had best appearance, aroma and acceptability and retained these well until day 4. Fresh-cut Brazilian fruit also displayed good initial quality, but lost this more rapidly. Fresh-cut Italian melons were positioned lower down towards the poorer end of the axis plane from the start, characterised as having reduced visual appeal and overall acceptability.

4. Discussion

4.1. Processes of deterioration

The PCA plots combined sensory and instrumental measurements of quality to provide "maps" of deterioration of fresh-cut fruit. The general pattern was loss of initial high sensory scores and the concurrent development of poor quality attributes during storage: off-odours, increased cell permeability and tissue breakdown, translucency, loss of firmness and high microbial growth. Flesh translucency is apparent when the cellular spaces are filled with liquid, giving tissues a more vitreous appearance (O'Connor-Shaw et al., 1994; Chen and Paull, 2001; Montéro-Calderón et al., 2008). In the current PCA plots, this was recorded as increasing lightness and greenness/yellowness in fresh-cut pineapple and kiwifruit. Translucency was usually followed by development of off-odours (melon) and browning at cut edges (pineapple). In general, tissue breakdown and cell leakage, reported as increased drip-loss, cell permeability and exudate levels, correlated well with increased microbial growth and development of off-odours. Products of microbial spoilage and fermentation result in aroma and flavour defects of fresh-cut fruits, during MA storage (Carlin et al., 1989, 1990). High CO_2 atmospheres, as observed in fresh-cut strawberry packs, can have contradictory effects on quality as they can damage product firmness but may also reduce bacterial and fungal growth, depending on the product in question (Carlin et al., 1990; Babic et al., 1993; Madrid and Cantwell, 1993; Barber et al., 2000).

4.2. Effects of fruit type, cultivar and origin

The relative importance of these different processes of deterioration varied with fruit type, and the rates of quality change during storage varied with fruit type, cultivar and geographic origin. Deterioration in fresh-cut pineapple was primarily in appearance, firmness and aroma coupled with an increase in browning, flesh softening, drip-loss and translucency, and development of off-odours. This is in line with degradative processes known to occur during storage which can cause tissues to discolour and loose moisture (Saltveit, 2000; Gil et al., 2006; Ártés et al., 2007). When the same cultivar was compared from two geographic origins, the patterns and rates of deterioration were similar, though there was a consistent difference in quality throughout.

In fresh-cut strawberry, the plots showed that deterioration was related to loss of firmness/increased cell permeability, weight loss, mould growth and off-flavour development, and that quality loss was rapid in the early stages of storage, between day 1 and day 4. When strawberries from different sources were compared, most were similar in their pattern and rate of deterioration, but Irish grown '*El Santa*' deteriorated faster than the other samples. Wright and Kader (1997) reported that the visual quality of strawberries decreased during 7 day storage, and regardless of packaging film and cultivar, decreased in firmness (Rosen and Kader, 1989), with shelf-life limited by discolouration, decay and/or visible microbial growth (Barth et al., 2009).

For fresh-cut kiwifruit, quality losses were associated with a severe loss in firmness (to a mushy consistency) and appearance (colour loss and translucency) coupled with a loss of aroma. In fleshy fruits which ripen during storage, the degradation of chlorophyll is more pronounced with concurrent decreases in total carotenoids (Lodge and Perera, 2011). Plots for fruits of the same cultivar but from different sources, showed that New Zealand fruit had better quality and slower deterioration than fruit grown in Brazil or Italy. The different extremes of quality change could be attributable to harvest seasons, in that kiwifruit from Italy could be stored for up to 1 year or freshly harvested, depending on when they were purchased within season, while kiwifruit from New Zealand could be stored for up to 6 months before purchased. This will be covered in more detail in paper II (Finnegan and O'Beirne, 2014).

In the case of cantaloupe melon, the plots showed that increased microbial growth, translucency, sponginess and off-odour development were characteristic of diminished quality. Fresh-cut melon lost its initial vibrant colour in favour of a more translucent, water-soaked appearance, especially where fruit was submerged in its exudate. Although the fruit pieces quickly lost their acceptability to panellists, they actually increased in instrumental firmness during storage. This was picked up by the PCA plot. Moreover, translucency, which is commonly reported in melon varieties (Portela and Cantwell, 1998, 2001; Aguayo et al., 2003) was apparent in this study and recorded by PCA as decreasing lightness (L^*) and orangeness (a^*). Fresh-cut melon (CH) produced from fruits grown in Italy were of lower quality than those from fruits grown in Costa Rica or Brazil. Yeast counts were high in fresh-cut cantaloupe melon packs (especially Italian fruit), and they developed noticeable off-odours which were successfully recorded by PCA. Babic et al. (1992) reported that large cell numbers of yeasts ($>10^5$ CFU g^{-1}) produce off-odours in fresh-cut produce. Beaulieu (2005) previously highlighted the difficulty in procuring cantaloupes of consistent quality, with changes in sugars, colour and volatile ester formation being the main reasons for raw material inconsistency during storage. These variations in quality may be partly attributed to storage conditions as previously discussed for kiwifruit, in addition to preharvest factors such as genotype, which will be discussed further in paper II (Finnegan and O'Beirne 2014).

Overall, there were significant effects of geographic origin of the fresh-cut kiwifruit and melons studied. Climate, cultural practices and postharvest systems have all been implicated as causes of product variability in fruit harvested from different production zones (Sideris and Krauss, 1933a,b; Leverington, 1968; Miller et al., 1998; Bergqvist et al., 2001; Mowat and Kay, 2007; Mowat and Maguire, 2007; Ritenour, 2010; Mazur et al., 2012).

Furthermore, strawberry varieties studied were ever-bearing ('*Camarosa*' and '*Festival*') and June-bearing ('*El Santa*' and '*Orly*') with each having individual production characteristics and intermittent seasonal effects. In addition, the production season of certain countries helps to explain cultivar effects as in Spain strawberry production starts in mid-Jan lasting until June while in Morocco starts late-Jan lasting until April. For cantaloupe melon and kiwifruit, differences in quality may be attributed to the difference in ripening behaviour of fruit from warmer climates (Marsh et al., 2004). Large changes in a number of chemical and physical parameters have been recorded not only in whole fruit (O'Connor-Shaw et al., 1994; Marsh et al., 2004) but also in the different tissue types within the fruit itself (Hallett et al., 1992; Wang et al., 1996; Montéro-Calderón et al., 2008). Higher respiration rates were recorded in the field for fruit growing at higher temperatures (Walton and DeJong, 1990) which appear to rapidly metabolise a particular acid pool when fruit are first placed in storage (Crisosto et al., 1984; Crisosto and Crisosto, 2001) therefore

helping to explain the different behaviour of fruits harvested from different environments. For kiwifruit, in adequate winter-chilling may be one of the main obstacles to productivity and quality which is of particular concern for '*Hayward*' which seems better suited to colder climates (Simonetto and Lamb, 2011).

4.3. Benefits of PCA plots

Recent studies have shown the effectiveness of PCA plotting in genetic classification, volatile aroma compound development, postharvest characterisation/spoilage and biodiversity studies (Rocha et al., 2010; Infante et al., 2011; Hurtado et al., 2012; Chen et al., 2013; Dong et al., 2013; El Kar et al., 2013; Wilson et al., 2013). The current PCA plots have produced useful information on quality and deterioration of fresh-cut fruit. They were effective in plotting initial quality, and quality differences between samples before and during storage. They highlighted the distinct processes of deterioration characteristic of each fruit type. They provided patterns of deterioration, indicating, for example, whether most deterioration occurred early or late in storage. They revealed similarities and differences in quality and patterns of deterioration resulting from cultivar or source of fruit. It is concluded that PCA can form the basis of more in-depth understanding of the effects of intrinsic and extrinsic factors on quality of fresh-cut fruits, and help optimise product quality.

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